

HIGH ALTITUDE CLEAR AIR TURBULENCE PROBABILITY BASED ON TEMPERATURE PROFILES AND RAWINSONDE ASCENSIONAL RATES

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ABSTRACT

Occurrences of clear air turbulence in the stratosphere at altitudes of 45,000 to 68,000 ft are analyzed in terms of observed variability in vertical temperature gradients and balloon ascensional rates based on nearby radiosonde data. While the magnitudes of both parameters are positively correlated with the probability of encountering turbulence, the temperature gradient variability has a higher correlation and appears to delineate more clearly the turbulent from the nonturbulent cases.

1. INTRODUCTION

The possibility that radiosonde balloon systems may experience large changes in rates of ascent while traversing regions of clear air turbulence was investigated by Hodge (1967). Pilot reports of turbulence over the altitude range 20,000 to 45,000 ft and within ± 3 hr and 100 n.mi. of regularly scheduled rawinsonde observations were plotted on rawinsonde ascensional rate profiles for a 5-day period during which a trough and associated jet stream progressed eastward across the southern United States. The analysis showed that the rawinsonde observations within regions of reported turbulence have much larger variations in ascensional rates than those outside the turbulent region. Prophet (1969) showed that, when thunderstorms occurred over a relatively dense network of special observing stations, some rawinsondes displayed large irregularities in ascensional rates in the lower stratosphere. A good correlation was found between the magnitude of these irregularities in ascensional rates and observed vertical gust velocities obtained by aircraft nearby.

The turbulence data used in this study were gathered during 1966–1967 as part of the U.S. Air Force High Altitude Clear Air Turbulence (HICAT) Program of collecting meteorological and turbulence data by U-2 aircraft in the altitude range 45,000 to 70,000 ft. Preliminary analyses of these data also indicated an apparent relationship between the occurrence of turbulence and variability in vertical temperature gradients. Ehernburger (1968), in an analysis of turbulence data experienced by XB-70 aircraft, presents temperature profiles that display alternating layers of lapse and inversion accompanying turbulence. However, an example of a smooth flight is characterized by a fairly uniform temperature profile.

This paper describes the results of a study to determine what sort a quantitative relationship exists, if any, between the probability of HICAT occurrence and associated magnitudes of observed variability in both rawinsonde

ascensional rates and vertical temperature gradients as observed at nearby stations.

2. HICAT AND RAWINSONDE ASCENSIONAL RATES

For this portion of the study, only data from HICAT flights conducted over the United States including Hawaii and Alaska were used. Original winds-aloft computation sheets (WBAN-20) were obtained from the U.S. Weather Bureau for 75 observing stations that satisfied the criteria of being within 100 n.mi. and ± 3 hr of a HICAT flight track. The aircraft encountered turbulence near 31 of the stations, and smooth flight conditions were found around the remaining 44. Wind data are tabulated on these sheets at height intervals averaging about 700 m or 2,000 ft. As the elapsed time since balloon release is also given for each level, a mean vertical velocity for each of the 11 to 12 height intervals between 45,000 and 68,000 ft was obtained and subsequently used to calculate a standard deviation of balloon ascensional rate for each rawinsonde observation.

In summarizing the data, the observed probability of encountering turbulence was figured for each 0.10 m sec^{-1} interval of σw_b . As some intervals contained none or only a few cases, an overlapping two-interval running mean probability was calculated. This smoothing reduced some of the variability; but even so, the correlation coefficient is only 0.45. A linear least-squares regression equation with 95 percent probability limits (plus and minus two standard errors of estimate σ_e) was calculated and is shown in figure 1. As may be seen, the probability of encountering turbulence increases gradually with increasing σw_b .

Hodge considers possible sources of errors that could cause variations in balloon ascensional rates and assigns a value of 25 percent or more for a deviation in a 2,000-ft layer to be significant. For a mean rise of 5 m sec^{-1} , the threshold value for a significant deviation in the mean layer speed then becomes 1.25 m sec^{-1} . For a sample of 10 layers, a deviation of this magnitude in the mean

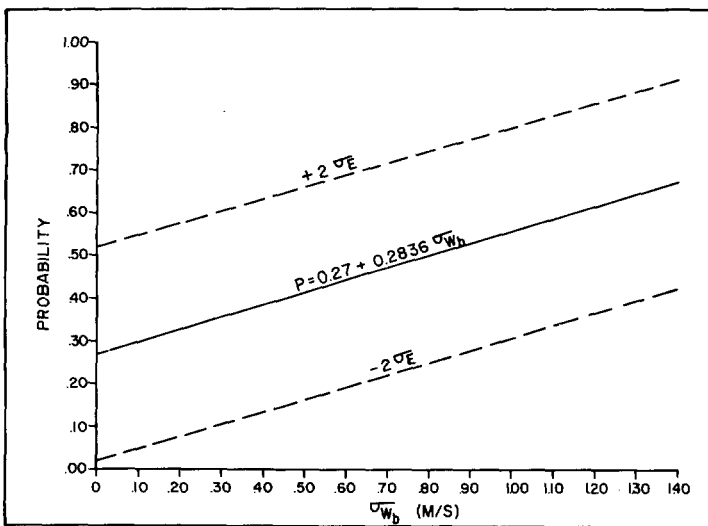


FIGURE 1.—Probability of encountering turbulence in the layer 45,000 to 68,000 ft as a function of the standard deviation of the rawinsonde balloon ascensional rate.

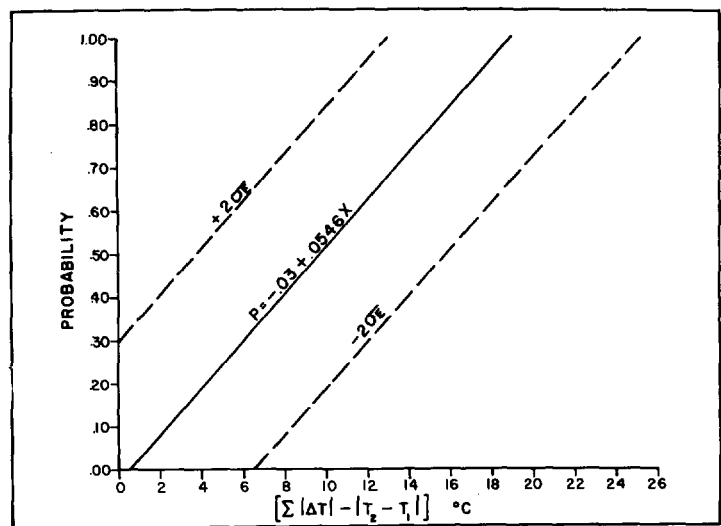


FIGURE 2.—Probability of encountering turbulence in the layer 45,000 to 68,000 ft as a function of the temperature gradient variability parameter.

layer speed can be associated with a σw_b , as low as 0.40 m sec^{-1} at the 1 percent level of significance. However, 45 percent of all turbulence cases were associated with σw_b values less than 0.40 sec^{-1} . In addition, in terms of actual numbers, there were more cases of no turbulence at higher values, specifically 19 cases with no turbulence and 17 with turbulence. Hence, the validity of a threshold value of 0.40 m sec^{-1} for σw_b cannot be verified from these data.

3. HICAT AND VERTICAL TEMPERATURE GRADIENTS

Analysis of HICAT turbulence data and reasonably concurrent radiosonde data shows a consistently close association between the occurrence of turbulence in the stratosphere and large changes in vertical temperature gradient. Conversely, smooth air is closely associated with nearly constant or at most only slightly varying vertical temperature gradients. Mitchell and Prophet (1969) suggest that such varying lapse rates may be associated with wave motion, and a turbulence model is proposed whereby values for incremental vertical RMS accelerations are calculated from the radiosonde temperature profile data. Their study suggested that a forecast of probability of encountering turbulence might be made based on the irregularities in the local vertical temperature profile.

For examining this relationship further, radiosonde data for 114 stations that satisfied the criteria of being within 100 n.mi. and $\pm 3 \text{ hr}$ of a HICAT flight were used in the analysis. These included many of the same U.S. stations used in the balloon ascensional rate study plus Southern Hemisphere stations in Australia and New Zealand. The HICAT aircraft encountered turbulence near 47 of these stations, while the remaining 67 were

associated with smooth flight conditions. Values for a temperature gradient variability parameter defined by $[\Sigma|\Delta T| - |T_2 - T_1|]$ were calculated from each sounding over either the 150- to 70-mb layer (approximately 45,000 to 60,000 ft) or 100- to 50-mb layer (approximately 53,000 to 68,000 ft) depending upon the aircraft flight altitude. The term $\Sigma|\Delta T|$ is the absolute value of the total temperature change through the layer regardless of sign, and T_1 and T_2 are the temperature at the lower and upper boundaries, respectively. A zero value is obtained in the event the temperature gradient is uniform throughout the layer. The observed probability of turbulence was calculated for each degree of the temperature parameter. Due to the small sample in some instances and to smooth the data, turbulence probabilities were computed based on an overlapping running mean 2° temperature interval. A linear regression equation was fitted to the data, and the resulting least squares curve is shown in figure 2 along with the 95 percent probability limits. The correlation coefficient of 0.62 is larger than for the balloon ascensional rate regression curve in figure 1. Also, the slope is much greater in this instance, thus helping to more clearly delineate the turbulent cases. As may be seen, the probability of turbulence increases rapidly with increase in total vertical temperature variability; and in this HICAT sample, turbulence was always encountered when the calculated temperature parameter equaled or exceeded 13°C . A total of 21 cases or 45 percent of all turbulence soundings fell into this category.

4. DISCUSSION OF SPECIFIC EXAMPLES

Examples of vertical temperature gradients and concurrent balloon ascensional rate data are presented to show that at least in some specific instances both param-

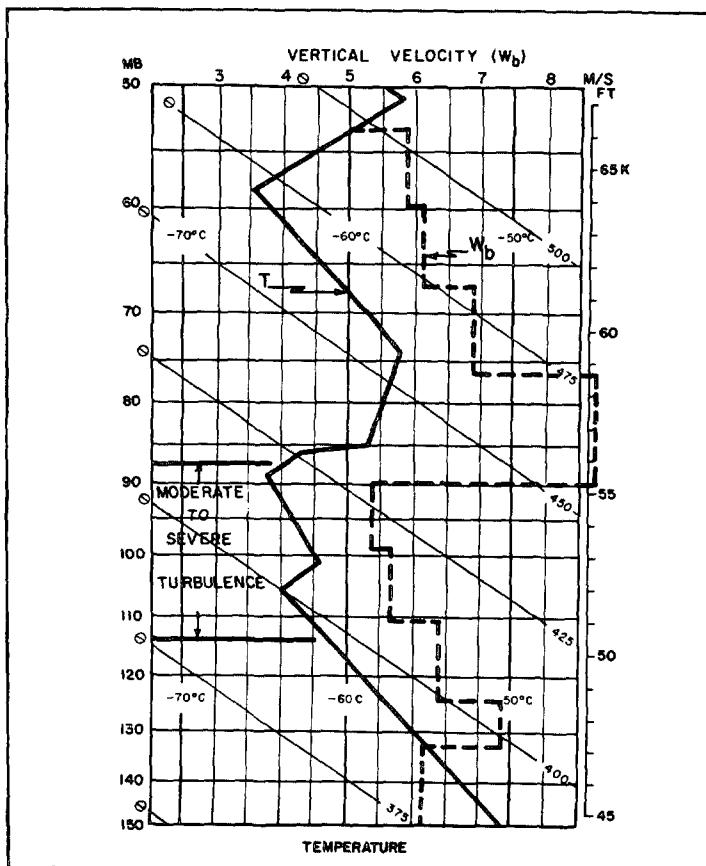


FIGURE 3.—Situation with moderate and severe turbulence near Albuquerque, N. Mex. Radiosonde temperature (T) and balloon ascensional rate (w_b) data taken at 00 GMT on Dec. 2, 1967.

eters indicated a high probability of turbulence when turbulence did indeed occur. Conversely, an example is presented in which neither parameter indicated a high probability of turbulence, and no turbulence was found. Examples are also given when one but not both parameters indicated that turbulence was probable.

The radiosonde data for a situation when severe turbulence occurred near Albuquerque is shown in figure 3. The temperature parameter is 26°C for the layer 100 to 50 mb and, according to figure 2, indicates 100 percent probability of turbulence. The balloon ascensional rate standard deviation σw_b was 1.02 m sec^{-1} , and variations as great as 3 m sec^{-1} occurred in the turbulence zone. According to figure 1, the least squares probability of turbulence based on the calculated value for σw_b is 56 percent, but with a possible range of 30 to 80 percent. The sounding was taken about 3 hr prior to the time of aircraft turbulence encounter.

The radiosonde data for a situation when light to moderate turbulence occurred near Las Vegas is shown in figure 4. In this case, the temperature parameter 150 to 70 mb is 13°C , which indicates (fig. 2) a 68 percent chance of turbulence. On the other hand, σw_b is only 0.38 m sec^{-1} with no large deviations between layers; and from figure 1, the least squares probability of turbulence is only 38 percent. In this case, the turbulence was encountered about 3 hr prior to the time of the sounding.

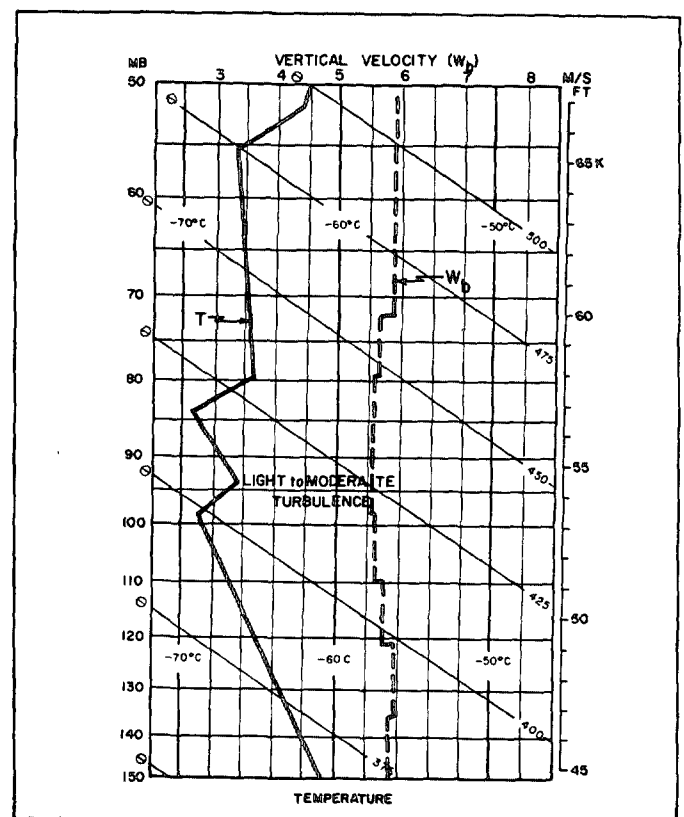


FIGURE 4.—Situation with light to moderate turbulence near Las Vegas, Nev. Radiosonde temperature (T) and balloon ascensional rate (w_b) data taken at 00 GMT on Apr. 2, 1966.

A situation with light turbulence east of Ely, Nev., and one in which the balloon ascensional rate standard deviation indicated a higher probability of turbulence than the temperature parameter is shown in figure 5. The least-squares probability of turbulence in the layer 100 to 50 mb is only 17 percent based on the 3.6°C temperature parameter. However, the least-squares probability of turbulence is nearly 50 percent based on the calculated σw_b value of 0.71 m sec^{-1} . The turbulence was encountered about 3 hr prior to the time of the sounding. Less than an hour later, a situation with no turbulence and one in which neither parameter indicates a high probability of turbulence is shown in figure 6 for Las Vegas. In this case, the temperature parameter in the layer 100 to 50 mb is zero, and σw_b is only 0.26 m sec^{-1} corresponding to a least squares turbulence probability of 35 percent.

5. SUMMARY

A summary of the occurrence of turbulence according to ten-percentile probability categories based on the least-squares temperature and σw_b parameters in figures 1 and 2 is shown in table 1. In general, it appears that the temperature parameter more clearly delineates the turbulent cases than does the standard deviation of the balloon ascension rate. This table is based on 65 soundings where both sets of data were available. Of these, 25 cases, or 35 percent of the total, were categorized as turbulent.

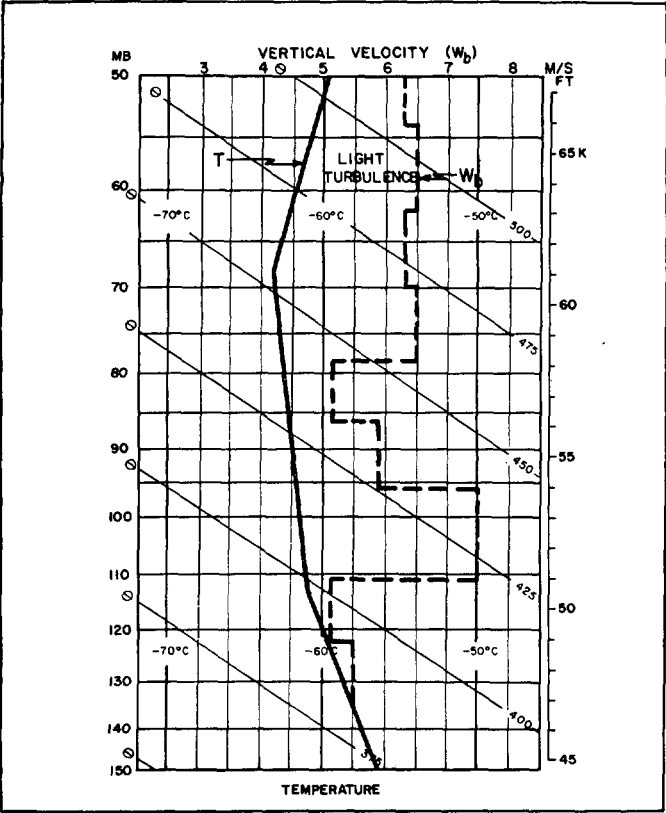


FIGURE 5.—Situation with light turbulence near Ely, Nev. Radiosonde temperature (T) and balloon ascensional rate (w_b) data taken at 00 GMT on Apr. 6, 1966.

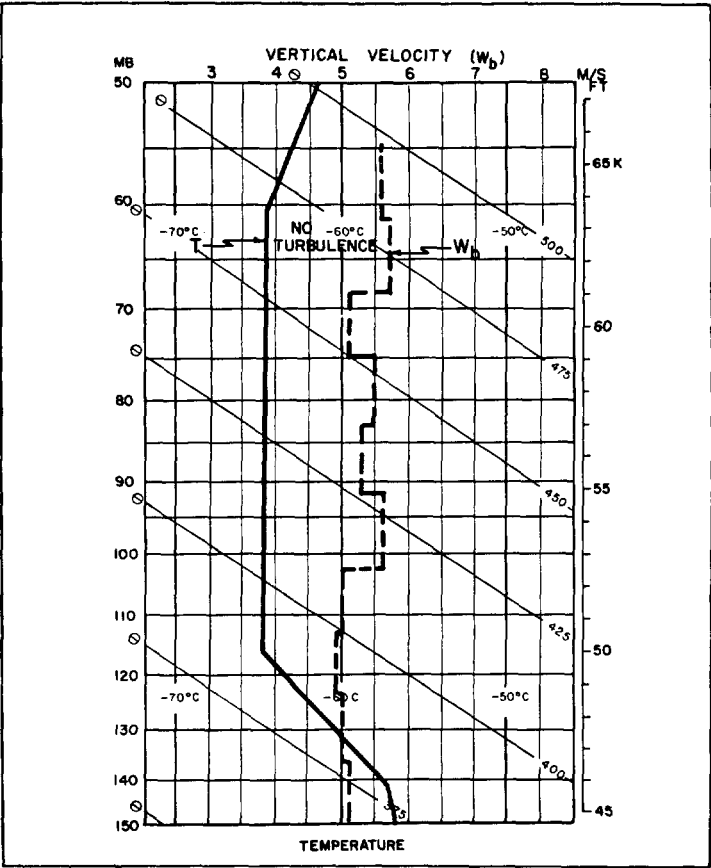


FIGURE 6.—Situation with no turbulence near Las Vegas, Nev. Radiosonde temperature (T) and balloon ascensional rate (w_b) data taken at 00 GMT on Apr. 6, 1966.

TABLE 1.—Percent of cases with turbulence according to categories of least-squares turbulence probability (P) based on temperature (T) and σw_b parameters

$P(\sigma w_b)$	$P(T)$ 0-0.10	0.11-0.20	0.21-0.30	0.31-0.40	0.41-0.50	0.51-0.60	0.61-0.70	0.71-0.80	0.81-0.90	0.91-1.00
0-0.10										
0.11-0.20										
0.21-0.30	0				0		0			
0.31-0.40	11	17	33	100	50	0	50	100		100
0.41-0.50	0	50	0		75	75	0	100	100	100
0.51-0.60			0				0		100	100
0.61-0.70										

A desirable further step in this analysis would be to test these relationships with an independent set of data. This, of course, can be accomplished by anyone who has access to current aircraft turbulence data obtained at heights above the tropopause.

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